Tilted-THP over Correlated Time-Varying MIMO Channels

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Abstract

In spite of good performance of Tomlinson-Harashima Precoding (THP) in MIMO systems, it suffers from some drawbacks, including modulo, shaping and power loss. Moreover, in time-varying MIMO channels, due to channel variations, there is some more loss in performance of THP. To overcome this problem, the Channel State Information (CSI) should be updated each (or some) intervals. Sending channel information for each time slot needs a high volume of feedback data from receiver to transmitter. In temporal correlated MIMO channels, it is possible to use the correlation property of the channel and hence compensating channel uncertainty by using lower feedback volume. According to this idea, a robust MIMO-THP is proposed in this paper for time-varying channels based on Minimum Mean Square Error (MMSE) criterion where it is assumed that the perfect CSI is only available at the beginning of each transmission block, and for the next symbols, the channel deviations are pre-equalized blindly. Moreover, the transmit power of the proposed robust MIMO-THP is reduced by using the Tilted constellation concept. This reduction in transmit power in time varying channels is translated into a reduction of Inter Channel Interference (ICI) between MIMO sub-channels and in addition compensates some of the THP's power loss. Our simulation results show that the proposed robust MIMO-THP outperforms the conventional MIMO-THP technique over correlated channels.

Keywords

MIMO Channels; Tomlinson-Harashima Precoder; Minimum Mean Squared Error (MMSE) Criterion; Time-Varying Channel; Tilted Constellation

Introduction

It is well known that the Multiple-Input Multiple-Output (MIMO) systems have higher capacity than the traditional single-input single-output (SISO) systems; however, to achieve this capacity, it is required to cancel the interference between sub-channels at the receiver side. To do this, some techniques as Tomlinson-Harashima Precoding has been proposed to pre-eliminate this interference [Windpassinger (2004)]. In general, the ability to reduce the sub-channels interference depends on the available amount of Channel State Information (CSI) at the transmitter side. The common way to obtain the CSI at the transmitter side is to estimate them at the receiver and feed them back to the transmitter through a feedback channel. However, this method has only good performance in flat fading MIMO channels, and it is not suitable for the case of time-varying MIMO channel [KhaleghiBizaki et al. (2010)] in which the THP parameters should be designed in each (or some) symbol time slot. However, this method seems to be very complicated and tends to produce high feedback data overhead. Therefore, in most of the papers, the channel is assumed to be static during one or several symbol intervals, but this assumption is less valid for practical scenarios and may reduce the performance of the system [KhaleghiBizaki et al. (2010)].

In some works, the time-varying nature of MIMO channels is discussed. In Fischer et al. (2002), the authors proposed a combined linear precoder and Space-Time Block Code (STBC) method which is designed for rapidly time-varying channels based on Minimum Mean Square Error (MMSE) criterion; however, their method has a complicated structure and needs many calculation to compute the combined precoder and STBC.

In Tong et al. (2011), the proposed linear precoding for time-varying channels based on the Conjugate Gradient (CG) method could reduce complexity of the system compared with the conventional approaches, while increasing the MSE.

In Kung et al. (2004), a recursive QR approach has been presented for designing of linear equalizer in time-varying frequency selective MIMO channels. However, their works need many computations and iteration to compute precoder coefficients.

In contrast to the previous works in which the linear precoder was taken into consideration, in Castro et al. (2005) an adaptive nonlinear precoder (i.e. the THP

precoder) was proposed for the frequency selective channel, which is optimized according to the updated CSI in every symbol time slot. This updating for each time slot needs a high volume of feedback data from receiver to transmitter.

In this paper, we extend the MMSE Tomlinson-Harashima precoder design concepts of Khaleghi-Bizaki et al. (2008) to the time-varying MIMO channels and introduce a robust MMSE-THP precoder which is robust against channel variations. The proposed method needs the CSI only at the first of each data blocks and blindly pre-equalizes the channel during the block based on the time correlation property of channel. In addition, Tilted constellation method of Kang et al. (2009), Kim & Lee (2013), Carolin & Johannes (2013) is used to reduce the transmit power of the proposed robust THP. The power reduction mitigates the Inter Channel Interference (ICI) between sub-channels and in addition recovering some of the THP's power loss. Consequently, this ICI reduction and power loss recovering cause the BER of system to be improved.

It should be noted that in the Tilted constellation of THP which is originally developed for SISO channels in Kang et al. (2009), by tilting or rotating the ordinary constellation by a proper angle, the transmit power is reduced. The appropriate angle is the one that minimizes the transmission power and it is chosen from a set of possible angles. This power reduction is greater at higher SNRs and shorter data block lengths. Since the transmitted power determines the slope of BER curves Kang et al. (2009), at these SNRs. a lower BER can be achieved with tilted-constellation THP. In our scheme, we extend this idea to MIMO channels and more over, for time-varying channels.

In the proposed Tilted-MIMO-THP, we use different angles for tilting the constellation at each antenna. Hence, we need to find a set of proper angles, which minimize the total transmitted power of all antennas. Appropriate angles then are sent to the receiver through a feed-forward link. We consider MMSE-MIMO-THP in our proposed method and develop the Tilted constellation method for it in the time-varying channels. The performance of the proposed method is studied in different symbol block lengths and different normalized Doppler frequency shifts. By simulations, it is shown that the proposed method has a good improvement in performance with respect to the previous works. The complexity of our proposed method is also investigated with respect to some previous methods. The material in this correspondence was presented in part at Khaleghi et al. (2012) and Khaleghi Bizaki et al. (2013).

This paper is organized as follows: section II describes the system model. Section III provides the detail of the proposed Tilted-MIMO-THP scheme. In section IV, computer simulations are conducted to evaluate performance of the proposed method. Finally, the conclusion is given in section V.

System Model

We consider a MIMO-THP broadcast communication system with n_T transmit antennas and n_R users each equipped with a single receive antenna. A block diagram of the proposed Tilted-MIMO-THP scheme is illustrated in Fig. 1 and briefly explained below.

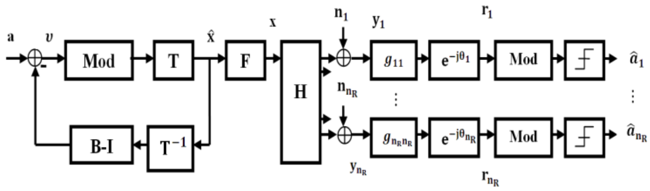

FIG. 1 PROPOSED MIMO-THP WITH TILTED CONSTELLATION IN DECENTRALIZED SCENARIO

The n_T dimensional vector a_t represents input symbol and signal $\hat{x}_t$ at time instant t, passing through feedback filter B_t, and tilt matrix T which is added to the intended transmit vector to pre-eliminate the interference from previous users. Then the resultant signal is fed to modulo-operator to keep the resultant symbols within the original constellation. The boundary region of the constellation is related to the modulation constellation, which for rectangular M-ary QAM modulation is considered to be $t = 2\sqrt{M}$ [Windpassinger (2004)]. Using tilted constellation, the signal constellation is further rotated by a set of appropriate angles, represented by the diagonal elements of tilting matrix T; to reduce the ICI and power loss of THP.

The output signal of tilted matrix is then passed through a unitary feed-forward filter to remove the residual interference. Finally, the precoded signal is sent through the MIMO channel. In view of the fact that all interferences are take into account when the transmit signal is calculated and subtracted at the transmitter side, The receivers are left with some simple operations including power scaling (i.e. the diagonal matrix G_t), de-modulo operation(to keep the received symbols within the original constellation), constellation tilting with reverse angle and a single

user detection. According to Fig. 1, the received signal can be represented as:

$$y_t = H_t x_t + n_t, \tag{1}$$

where $\boldsymbol{x}_t \in C^{n_T\times 1}$, $\boldsymbol{y}_t \in C^{n_R\times 1}$, $\boldsymbol{H}_t \in C^{n_R\times n_T}$ and $\boldsymbol{n}_t \in C^{n_R\times 1}$ represent the transmitted, received, channel fading coefficients and noise vectors, respectively (C denotes complex domain). The elements of the noise vector are assumed as independent complex Gaussian random variables with zero mean and variance σ_n^2, i.e. $n_t \sim CN(0, \sigma_n^2 I_{n_R})$.

In time-varying channel, it is assumed that the perfect CSI is known at the beginning of each data block, but not available during the block; meaning that it is desired to optimize THP at time t with the assumption that the outdated CSI, i.e. $H_{(t-\tau)}$, is available. $H_{t-\tau}$ corresponding to the channel state τ second earlier (i.e. the beginning of the block). For simplicity, we assume $\tau = lT_s$ where $l \le N$, and T_s and l represent the symbol time and number of symbols, respectively.

The outdated CSI $H_{t-\tau}$ can be obtained from H_t based on the correlated channel model as [Fischer et al. (2002)]:

$$H_t \sim CN(\rho_t H_{t-\tau}, (1-\rho_t^2)I), \tag{2}$$

where ρ_t is common time-correlation of the i.i.d. time-varying MIMO channel and defined as

$$\rho_t = E\{[H_t]_{i,j}[H_{t-\tau}]_{i,j}^H\} = R(\tau), \tag{3}$$

where $R(\tau)$ depends on the channel time-variation model.

As shown in Fig. 1, we use a titling diagonal matrix T in both feed-forward and feedback paths in the transmitter side as

$$T = \begin{bmatrix} e^{+j\theta_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{+j\theta_{n_T}} \end{bmatrix}. \tag{4}$$

It should be noted that this matrix is equal to an identity matrix in the conventional MIMO-THP (untitled MIMO-THP) systems.

For MMSE criterion, the error is defined as the difference between the effective data vector v_t and the data vector at the input of the decision modulo r_t as

$$e_t = r_t - v_t = [T^{-1}G_t H_t F_t - T^{-1}B]\hat{x}_t + \hat{n}_t, \tag{5}$$

where $\hat{n}_t = T^{-1}G_t n_t$ is the equivalent noise. Using MMSE criteria, this error is minimized as:

$$\underset{G_t,B_t,F_t}{\operatorname{argmin}} E_{H_t|H_{t-\tau}} \begin{cases} E_{a,x}\|[T^{-1}G_t H_t F_t - T^{-1}B]\hat{x}_t + \hat{n}_t\|^2 \\ \text{s.t.} \quad E\|x_t\|^2 \le P_T \end{cases} \tag{6}$$

where P_T is total transmitted power. Instead of solving (6), it is easier to use the orthogonallity principle [KhaleghiBizaki et al. (2008)]. In this case, the MMSE solution should satisfy:

$$E_{H_t|H_{t-\tau}}\{e_t {r_t}^H\} = 0. \tag{7}$$

Hence

$$G_t \phi_{rr,t} = B_t \phi_{\hat{x}r,t}, \tag{8}$$

where $\phi_{rr,t} = E_{H_t|H_{t-\tau}}\{e_t {r_t}^H\}$ and $\phi_{\hat{x}r,t} = E[\hat{x}_t r_t^H]$.

Using (1) the matrix $\phi_{rr,t}$ can be obtained as:

$$\phi_{rr,t} = E_{H_t|H_{t-\tau}}\{e_t {r_t}^H\} = E_{H_t|H_{t-\tau}}\{\sigma_{\hat{x}}^2 H_t {H_t}^H + \sigma_n^2 I\}. \tag{9}$$

Calculation of conditional expectation in (9) is not straightforward. We consider an approximate solution by considering the channel H_t as $H_t = \bar{H}_t + \Delta_t$ where

$$H_t = \bar{H}_t + \Delta_t = \rho_t H_{t-\tau} + \sqrt{(1-\rho_t^2)}E_t, \tag{10}$$

where $\rho_t = R(\tau) = J_0(2\pi f_D \tau)$ is the correlation coefficient between the two instant t and $t-\tau$, where J_0 is the zeroth order Bessel function of the first kind and f_D is maximum Doppler frequency, and E_t is the circularly symmetric complex Gaussian matrix with i.i.d. entries ($E_t \sim CN(0, I)$). Hence, relation (9) can be written as:

$$\begin{aligned} \phi_{rr,t} &= E_{H_t|H_{t-\tau}}\{\sigma_{\hat{x}}^2(\bar{H}_t + \Delta_t)(\bar{H}_t + \Delta_t)^H + \sigma_n^2 I\} \\ &= \sigma_{\hat{x}}^2 \bar{H}_t {\bar{H}_t}^H + C_{\Delta_t} + \sigma_n^2 I \end{aligned} \tag{11}$$

where we assumed $C_{\Delta_t} = (1-\rho_t^2)I$. Also, to calculate $\phi_{\hat{x}r,t,}$ we can substitute (11) and (12) in (8), then we have:

$$\begin{aligned} \phi_{\hat{x}r,t} = E[\hat{x}_t r_t^H] &= E_{H_t|H_{t-\tau}}\{E_{a,\hat{x}}[\hat{x}_t {r_t}^H]\} \\ &= E_{H_t|H_{t-\tau}}\{E_{a,\hat{x}}[\hat{x}_t {\hat{x}_t}^H {F_t}^H {H_t}^H]\} \\ &= E_{H_t|H_{t-\tau}}\{\sigma_{\hat{x}}^2 {F_t}^H (\bar{H}_t + \Delta_t)^H\} \\ &= \sigma_{\hat{x}}^2 {F_t}^H {\bar{H}_t}^H \end{aligned} \tag{12}$$

$$F_t^H = B_t^{-1} G_t (\bar{H}_t {\bar{H}_t}^H + C_{\Delta_t} + \zeta I){\bar{H}_t}^{-H}, \tag{13}$$

where $\zeta = \sigma_n^2/\sigma_x^2$. Since F_t is considered to be unitary matrix, we obtain

$$S_t {S_t}^H = \left(\bar{H}_t {\bar{H}_t}^H + \zeta I + C_{\Delta_t}\right) {\bar{H}_t}^{-H} {\bar{H}_t}^{-1} \left(\bar{H}_t {\bar{H}_t}^H + \zeta I + C_{\Delta_t}\right), \tag{14}$$

where we assumed $S_t = G_t^{-1} B_t$ in which S_t can be obtained by Cholesky factorization of (14). The feedback matrix B_t, the feed-forward filter matrix F_t and the diagonal scaling matrix G_t can be expressed as follow [Kim & Lee (2013)]:

$$\begin{aligned} G_t &= \operatorname{diag}\left(1/s_{11}, \ldots, 1/s_{N_t N_t}\right) \\ B_t &= G_t S_t \\ F_t &= (\rho_t H_{t-\tau})^{-1}\left({\rho_t}^2 H_{t-\tau} {H_{t-\tau}}^H + \zeta I + (1-\rho_t^2)I\right){S_t}^{-H} \end{aligned} \tag{15}$$

If the channel is assumed to be quasistatic, i.e., $\rho_t \to 1$, and the rotation matrix is assumed to be unitary, i.e., $T \to I$, the above equation convert to what is considered as conventional MMSE-THP in this paper.

Tilted MIMO-THP

As mentioned before, in the general model of Fig. 1,

each element of the diagonal tilting matrix T determines the rotation angle of its corresponding antenna signal.

In conventional THP technique, the main constellation is only extended by a modul operator on its boundary regions, however, in the tilted-THP, the signal constellation is further rotated by a set of appropriate angles. In order to do this, a block of symbol with length N is divided into n_T groups (equal to the number of transmitting antennas) each of length N/n_T; Then, every group of symbols which are transmitted from one of the antennas, the transmitter chooses an appropriate angle from a set of possible angles in such a way that the transmitted power is minimized based on some criteria. From Kang et al. (2009), the ordinary constellation is tilted by Q possible angles as $\theta_q, q = 1, \dots, Q$. Then, the optimal angle θ_q^* is selected based on the following equation:

$$q^* = \arg\min_{q=1,\dots,Q} \left\| \mathrm{Mod}[a - ie^{-j\theta_q}] \right\|, \qquad (16)$$

where a is the group of symbols in each transmitting antenna and i illustrates the interference sequence at each antenna due to the previous antennas and is calculated similar to the conventional THP. The difference between the conventional (i.e. untitled) and tilted THP is in rotating of the transmitted signal of the previous antennas by their optimal angles. Transmitted power and resulting optimal angle of the each antenna are calculated as [Kang et al. (2009)]:

$$P_{tilted}(Q) = E\left\{ \min_{q=1,\dots,Q} X_q \right\}$$
$$X_q = \frac{1}{N}\sum_{i=1}^{N} \left\| \mathrm{Mod}[a - ie^{-j\theta_q}] \right\|^2 \qquad (17)$$

Symbols a_1 transmitted from first transmit antenna are not affected by any interference signal, that's why we transmit a_1 without any interference, with optimal tilted angle θ_1 that results from the minimized transmitted power for first antenna as:

$$x_1 = a_1 e^{j\theta_1}. \qquad (18)$$

For a_2, which is transmitted from second antenna, the optimal transmit angle is achieved by computing the minimum transmitted power similar to the a_1 but here, there is interference due to the a_1 and hence

$$x_2 = (\mathrm{Mod}(a_2 - b_{21}x_1 e^{-j\theta_2}))e^{j\theta_2}. \qquad (19)$$

Similarly, for the kth antenna, we have

$$x_k = \left(\mathrm{Mod}\left(a_k - \sum_{j=1}^{k-1} b_{kj} x_j e^{-j\theta_k} \right) \right) e^{j\theta_k} \qquad (20)$$

where θ_k is the optimal tilted angle for the kth antenna.

At the receiver side, the received signal for the kth antenna can be shown as,

$$r_k = (b^k x + n_k)\, e^{-j\theta_k} \qquad (21)$$

Where b^k denotes the kth row of matrix B_t. By using (20), relation (21) can be written as,

$$r_k = \left(x_k + \sum_{j=1}^{k-1} b_{kj} x_j + n_k \right) e^{-j\theta_k} \qquad (22)$$

Since $b_{kk} = 1$, hence after modulo operator we obtain

$$\begin{aligned} \hat{a} = \mathrm{Mod}(r_k) &= \mathrm{Mod}\left((a_k e^{j\theta_k} - \sum_{j=1}^{k-1} b_{kj} x_j + \sum_{j=1}^{k-1} b_{kj} x_j \right. \\ &\qquad \left. + n_k) e^{-j\theta_k} \right) \qquad (23) \\ &= \mathrm{Mod}\big((a_k e^{j\theta_k} + n_k) e^{-j\theta_k} \big) \\ &= \mathrm{Mod}\big(a_k + n_k e^{-j\theta_k} \big) \end{aligned}$$

As shown in the tilted constellation case, the matrix B_t is similar to the untited-MIMO-THP case; and the difference is only in rotation of the phase of the noise. Since the noise has circularly symmetric complex Gaussian distribution, therefore the relations and results for the decomposition of matrices in the tilted constellation case are similar to the conventional case.

If the tilted constellation is utilized to detect the original symbol directly, the performance will be degraded due to rotation and reduction of minimum distance between symbols. Hence we should send the optimal angles to the receiver to detect the desired symbols. In the receiver, the symbol demodulator at first reversely rotates the received signal for each antenna and then detects symbols in a way similar to the conventional THP.

Now, we discuss the complexity of the proposed method. It is realized that the proposed method add some parts to the conventional THP method. To compare the complexities of the proposed method and the conventional THP, we only consider those parts that are changed in our method. Any plus and minus operation is assumed as one calculation. For example, for the case of $n_R = n_T = 4$, the complexity of the conventional THP is 15n at the transmitter side and 8n at the receiver side while for the proposed Tilted-THP method this complexity is 25n at the transmitter side and 12n at the receiver side ,where $n = N/n_T$ is the length of the input symbol to each antenna. As it can be seen that the increased complexity is suitable. On the other hand, as shown in the next section in simulation results, the performance gain that we attain by the proposed method is more considerable with respect to the above complexity increasing.

Simulation Results

We assume a MIMO-THP system with 4 transmit and 4 receive antennas and 4-QAM modulation; then use (10) to simulate and model the channel from outdated CSI; as well normalized Doppler frequency $f_D T = 0.001$ and $f_D T = 0.005$ and $f_D T = 0.01$ for modeling of the slow, medium and fast time varying channel, respectively[KhaleghiBizaki et al. (2010)].

Fig. 2 shows the transmitted power of MMSE-THP system versus the number of tilted angles. In this figure, the SNR is assumed to be 20 dB. It can be seen that by increasing the number of available tilted angles, the transmitted power reduces until a constant as floor. This saturation is done due to that the matrix F is supposed to be unitary. Also, it can be seen that by decreasing the block length, the power reduction will be more and the power reaches faster its floor. For example, the transmitting power for the conventional MIMO-MMSE-THP is 4.91 but for the tilted constellation and with the similar condition, that decreases to 4 and 4.24 when the block length increases to5 and 10, respectively.

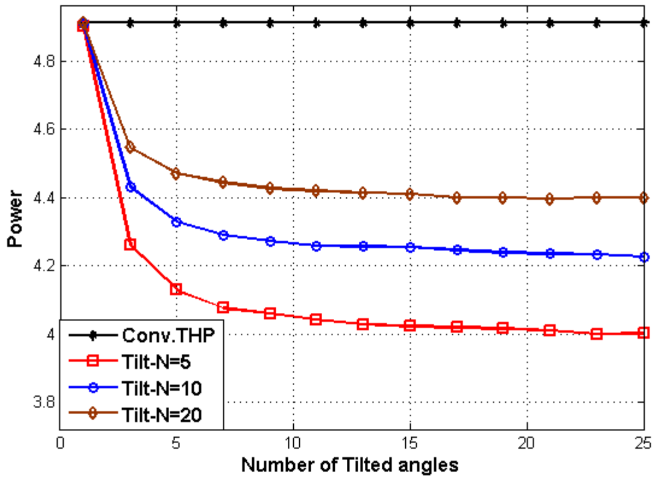

FIG. 2 TRANSMITTED POWER VS. THE NUMBER OF TILTED ANGLES IN DIFFERENT BLOCK LENGTH N=5,10,20. (SNR=20dB, Nt=Nr=4, 4QAM).

Fig. 3 shows BER vs. SNR for several block length and different normalized Doppler frequencyin theMIMO-MMSE-THP. It can be observed that the performance is improved in all block lengths compared to that in the conventional case, especially for high SNRs. This figure shows that the power reduction is greater for smaller blocks lengths. In addition, for the smaller normalized Doppler frequency, BER reduction is more. The result demonstrates that our proposed method has better performance in slow time-varying channels with respect to the fast time-varying channels.

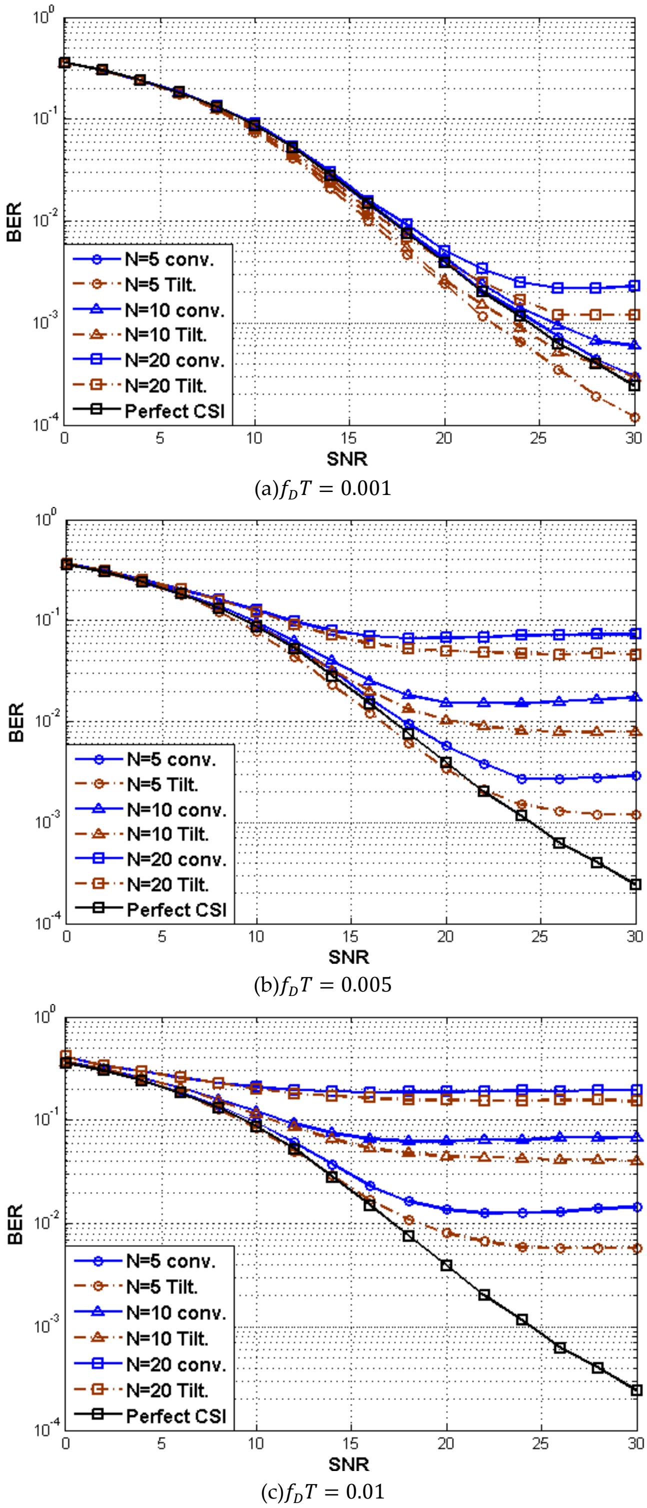

FIG. 3 BER VS. SNR AND SEVERAL BLOCK LENGTH AND NORMALIZED DOPPLER FREQUENCY IN MIMO-MMSE-THP

Conclusions

In this paper, we proposed a robust MIMO-THP scheme for time-varying channels based on MMSE criterion, which uses outdated CSI and correlation characteristic of channels to calculate the precoder coefficients. In the proposed robust method, the transmit power was minimized by using the Tilted

constellation method. The power minimization causes ICI reduction between sub-channels and recovers some of the THP's power loss. Consequently, this ICI reduction and power recovering result led to BER improvement, especially at high SNRs. The transmission power has reduced further by utilizing more tilted angles and smaller symbol block length. In addition, it was demonstrated that the achieved performance gain by using the proposed method is more considerable with respect to its higher complexity so as to avoid changing the complexity to n^2 or higher order. The tilted angle sends to the receiver so as to be known for the receiver.

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